or displacement measurements from the signal of an interferometric parameter and using a time domain based analysis. This family is described in relation to FIGS. **9**A-C and **10**. The methods and devices make use of a sinusoidal modulation of a bias current of the laser diode and detects resulting effects in an interferometric parameter of a photodetector associated with the laser diode.

[0141] In this second family of embodiments, a laser light source, such any of the VCSELs described in FIGS. **4**A-D, is used to direct laser light toward the location on the user's head. For simplicity of explanation only for this family of embodiments, the laser light source(s) will be assumed to be VCSEL(s). One skilled in the art will recognize how the embodiments may make use of other types of lasers or light sources that undergo self-mixing interference. In this second family of embodiments, there may be one or more photodetectors associated with each VCSEL, at least one of whose output parameters is correlated with a property of the self-mixing of the laser light that arises when some of the laser light emitted from the VCSEL diode is received back into the VCSEL diode after reflection from a target. In some embodiments, the photodetector is integrated as part of the VCSEL, such as in FIG. **4**A. In other embodiments, the photodetector may be separate from the VCSEL, as in FIG. **4**B. Instead of, or in addition to, an output of such a photodetector, some embodiments may measure another interferometric property of the VCSEL diode, such as a junction voltage.

[0142] The self-mixing interference effect contains at least two contributions: a first contribution from internal an electric field existing within the VCSEL diode and a second contribution from reflections from the target coupled back into the VCSEL diode, as indicated in FIG. **4**B. The second contribution enters the laser cavity phase shifted from the first. The radian value of the phase shift can be expressed as $\Delta\varphi=2\pi[2L \bmod \lambda]$, or equivalently as

$$2\pi\left(\frac{2L}{\lambda}-\left\lfloor\frac{2L}{\lambda}\right\rfloor\right),$$

where Δ is the wavelength of the laser light.

[0143] The bias current of a VCSEL diode may be driven by electronics, or other means, to include a superimposed sinusoidal modulation component, to have the form $I_{BIAS}\propto 1+\beta \sin(\omega_m t)$, where β is typically less than 1, and ω_m is the radian modulation frequency. The radian modulation frequency ω_m is much less than the frequency of the laser light. When a VCSEL diode is driven with such a bias current, the phase of the optical feedback light returning from the target upon reflection is such that $\Delta\varphi\propto a+b \sin(\omega_m t)$, for constants a and b. Certain specific forms for constants a and b for some embodiments will be presented below.

[0144] When the two contributions coherently interfere inside the laser cavity, the phase shift between them can cause their electric fields to interfere, either destructively or constructively. As a result, an output current of the photodetector can have the form $I_{PD}\propto[1+\delta \cos(\Delta\varphi)]$ in response to the similarly evolving optical output power of the VCSEL diode.

[0145] The Fourier series expansion of the function $\cos(a+b \sin(\omega_m t))$ has the form $\mathcal{F}\{\cos(a+b \sin(\omega_m t))\}=J_0(b)\cos(a)-2J_1(b)\sin(a)\sin(\omega_m t)+2J_2(b)\cos(a)\cos(2\omega_m t)-2J_3(b)\sin(a)\sin(3\omega_m t)+$higher order harmonics, where J_k indicates the Bessel function of the first kind of order k. So for the situation above of a sinusoidally modulated bias current of a VCSEL, the photodetector output current has a harmonics of the radian modulation frequency that can be selected by filtering, and the respective coefficient values that can be determined by demodulation, as explained in relation to FIGS. **9**A-C and **10** below.

[0146] For a target that had an initial distance L_0 from the VCSEL diode, and which has undergone a displacement of ΔL from L_0, the constants a and b above in some cases are given by:

$$a=[4\pi(L_0+\Delta L)/\lambda],\text{ and } b=[-4\pi\Delta\lambda(L_0+\Delta L)/\lambda^2].$$

[0147] Certain specific forms of the expansion for I_{PD} may thus be given by:

$$\begin{aligned}I_{PD} \propto \text{Baseband Signal} &- 2J_1\left[\frac{-4\pi\Delta\lambda L_0}{\lambda^2}\left(1+\frac{\Delta L}{L_0}\right)\right]\sin\left(\frac{4\pi\Delta L}{\lambda}\right)\sin(\omega_m t) + \\ &2J_2\left[\frac{-4\pi\Delta\lambda L_0}{\lambda^2}\left(1+\frac{\Delta L}{L_0}\right)\right]\cos\left(\frac{4\pi\Delta L}{\lambda}\right)\cos(2\omega_m t) - \\ &2J_3\left[\frac{-4\pi\Delta\lambda L_0}{\lambda^2}\left(1+\frac{\Delta L}{L_0}\right)\right]\sin\left(\frac{4\pi\Delta L}{\lambda}\right)\sin(3\omega_m t) + \ldots\end{aligned}$$

[0148] By defining a Q-component of I_{PD} as a low pass filtering and demodulation with respect to the first harmonic, i.e. $Q\propto \text{Lowpass}\{I_{PD}\times\sin(\omega_m t)\}$, and an I-component as a low pass filtering and demodulation with respect to the second harmonic, i.e. $I\propto \text{Lowpass}\{I_{PD}\times\cos(\omega_m t)\}$, one can obtain a first value

$$Q \propto \sin\left(\frac{4\pi\Delta L}{\lambda}\right),$$

and a second value

$$I \propto \cos\left(\frac{4\pi\Delta L}{\lambda}\right).$$

Then one can use the unwrapping arctan function (that obtains an angle in any of all four quadrants) to obtain the displacement as

$$\Delta L = \frac{\lambda}{4\pi}\arctan(Q/I).$$

[0149] In a modification of this implementation of the low pass filtering and demodulation, a Q'-component of I_{PD} can be defined as a low pass filtering and demodulation with respect to the third harmonic, i.e., $Q'\propto \text{Lowpass}\{I_{PD}\times\sin(3\omega_m t)\}$. This can then be used with the I-component derived by filtering and demodulation at the second harmonic, as above, to obtain a modified first value

$$Q' \propto \sin\left(\frac{4\pi\Delta L}{\lambda}\right),$$